National Aeronautics and Space Administration

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All four MMS observatories stacked and getting ready for launch. The payload was successfully launched on March 12, 2015 from Cape Canaveral Air Force Station, Florida

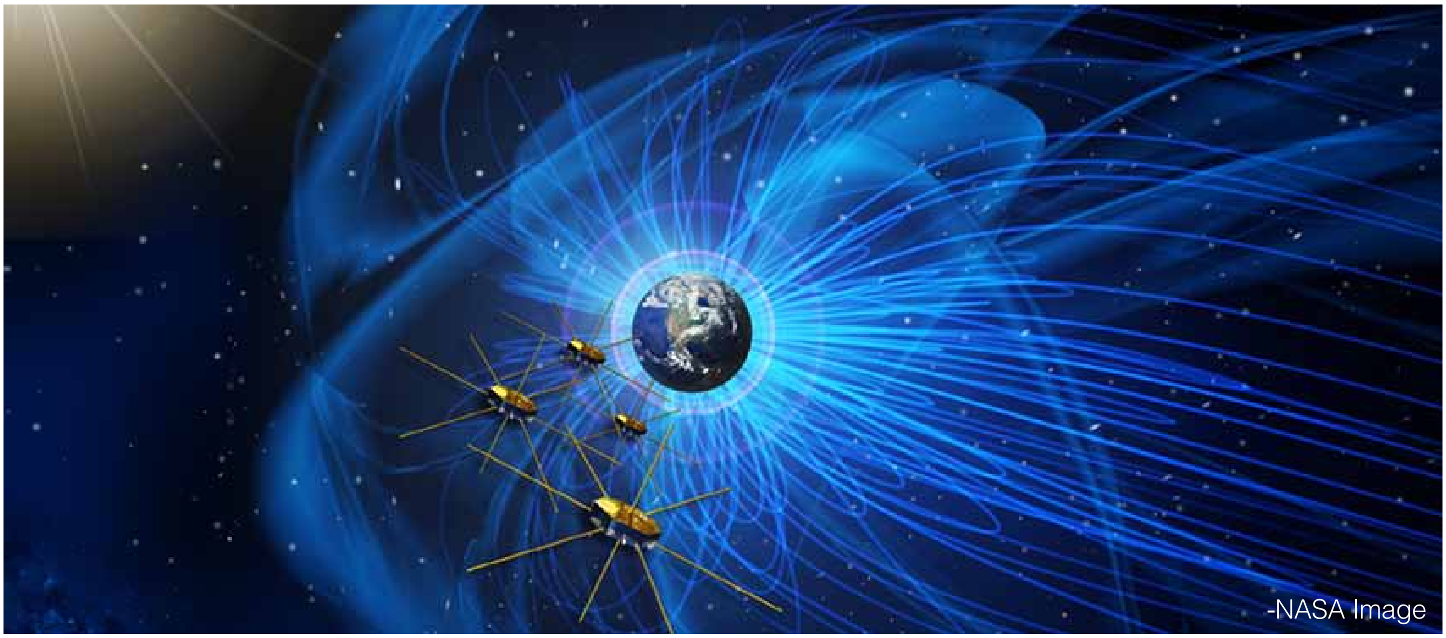
Magnetospheric Multiscale Mission

Contents

View of all four spacecraft in the MMS Cleanroom getting prepared for stacking operations.
-NASA/Chris Gunn

From the Chief

Nona Cheeks
Chief, Innovative Technology Partnerships Office (Code 504)
NASA Goddard



NASA Goddard Space Flight Center has done some impressive things over the years. Our record of innovation and accomplishment covers decades of ground-breaking missions, research, and operations. This issue of Tech Transfer News features one of Goddard's most impressive missions to date: the MMS Mission (Code 461). Comprised of four separate-but-identical spacecraft that fly in tetrahedral formation, the MMS Mission turns the Earth's magnetosphere into a laboratory to study the science of magnetic reconnection. We are also extremely pleased to present interviews with a number of the Goddard scientists, engineers, and project managers who made MMS possible.

Technologies in this issue will highlight the innovations in spacecraft observatories, flight dynamics, and data systems. Since magnetic reconnection and the science behind MMS impacts space weather, commercial and governmental markets concerned with space assets stand to benefit from the results of the mission. While MMS is primarily a research endeavor, the technologies described in the following pages have commercialization potential beyond future NASA missions.

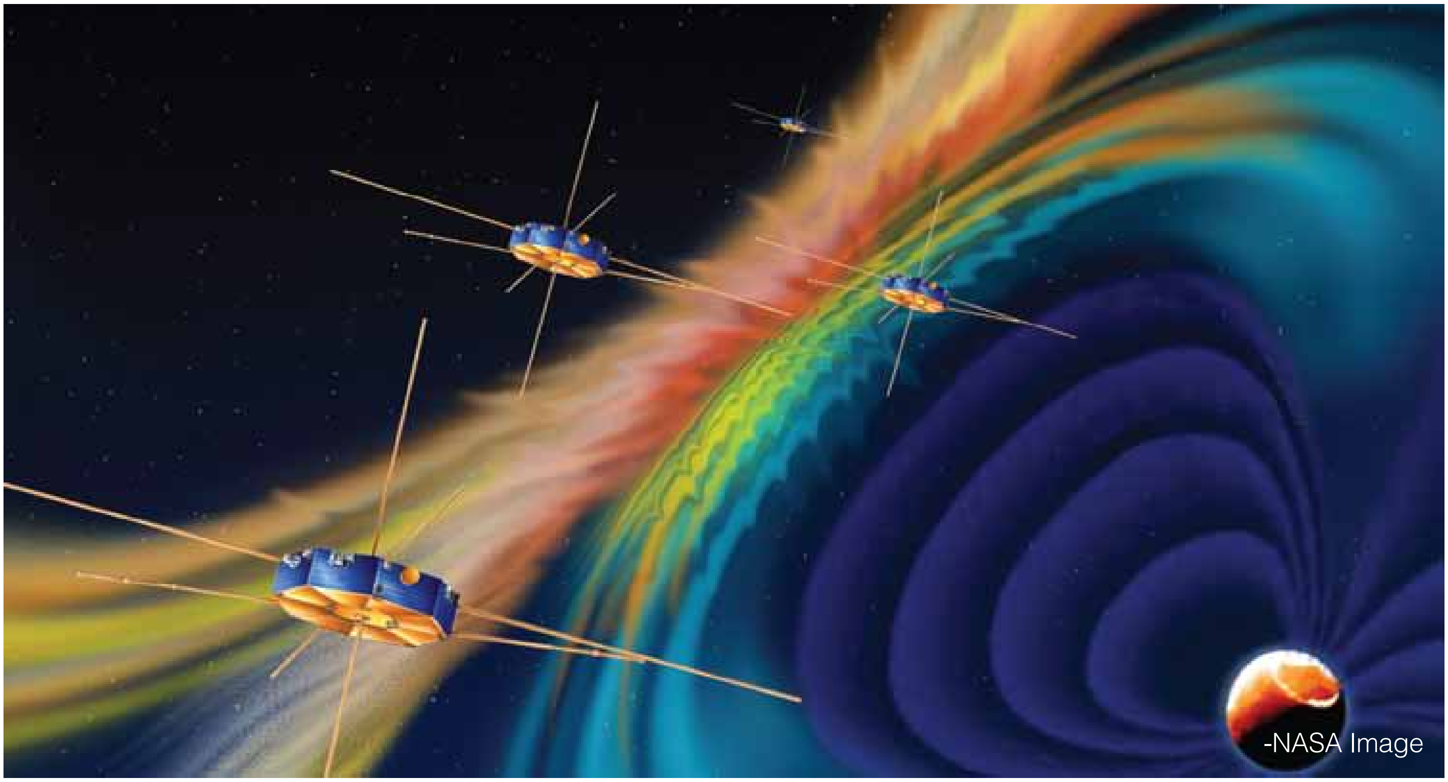
An example of such a tech transfer opportunity can be found in the Goddard designed and built Navigator (GSC-16754-1) for the MMS spacecraft. Taking advantage of existing satellites, the Navigator uses innovative technology to detect GPS signals while MMS spacecraft fly far above the current limit of GPS positioning. As with all MMS technologies, this success is not just measured by a single spacecraft, but by four flying together.

Building four identical spacecraft simultaneously is an immense challenge for a multitude of reasons. You will hear this echoed by the MMS team members interviewed in this issue as it pertains to all facets of the mission. You will also hear how working together at Goddard, and with numerous partners from national and international institutions, the MMS team met all of the challenges and surpassed expectations. With science operations getting started on the mission now that the commissioning phase is complete, MMS will continue to impress and represent NASA Goddard's tradition of achievement.

Nona Cheeks

Chief, Innovative Technology
Partnerships Office (Code 504)
NASA Goddard

MMS Mission Overview



The MMS Mission is one of NASA Goddard's most impressive accomplishments. Building four spacecraft simultaneously, integrating over 100 scientific instruments, and flying in formation to capture the split-second data of magnetic reconnection are a few of the feats to be featured in this issue. Overall, we will focus on three primary technology areas: observatories, data, and flight dynamics. You will be introduced to the major challenges and innovations in these areas, and then read interviews from NASA Goddard personnel--managers, engineers, and scientists--directly involved with the MMS Mission.

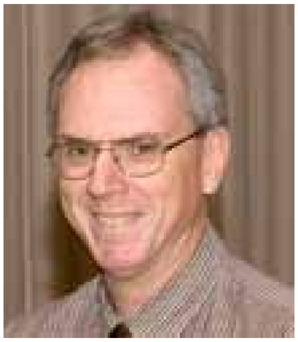
The science behind MMS is not easy for a lay reader to grasp at first glance. With such a complex scientific phenomenon at work, NASA Goddard has produced a series of videos to explain the mission to the public. MMS was also featured on NASA EDGE. Our hope is that this issue of Tech Transfer News can highlight the innovations and opportunities made possible by the mission. Before we delve into our technology areas, however, let's take a quick look at the main scientific objectives driving this exciting research.

NASA Goddard's MMS Mission website, http://mms.gsfc.nasa.gov/, promotes the "Earth's magnetosphere as a laboratory to study the microphysics of magnetic reconnection." Launched successfully on March 12, 2015, the mission is finishing its Commissioning (Phase D) and transitioning to Operations on September 1, 2015. The secret of magnetic reconnection is the interaction between magnetic fields from the Earth and the Sun. At stake in this process is the energy that is stored and released through magnetized plasma, which has never been closely studied due to the high level of difficulty in capturing the right data. The electron diffusion region (EDR), where reconnection occurs, is thin, fast moving, and largely unpredictable. While NASA spacecraft have encountered the phenomenon before, instruments were not fast enough to record sufficient data for study. One of the many innovations on MMS is data capturing at speeds 100 times faster than previous missions.

The EDR is also three dimensional, which necessitated innovative flight dynamics and a novel tetrahedral array of the four MMS spacecraft. Positioning the spacecraft required a novel Navigator system, designed and executed in-house at Goddard, which uses GPS signals in a manner never before achieved by spacecraft flying above GPS satellites. This Navigator technology has already been licensed and commercialized, and will be featured later in the magazine.

With so many satellites already in orbit, and only more to come as both governments and businesses seek to take advantage of big data and communications technologies, the intricacies of space weather can have a dramatic impact on satellite performance. The MMS Mission will gather much needed data on plasma behavior within the EDR, and help solve the mysteries of magnetic reconnection. By learning more about this powerful space weather phenomenon, scientists hope to pave the way for better prediction and management technologies that will protect the space assets of the future.

Dr. Thomas Moore, PhD
Project Scientist, MMS



Code: 670

Years with NASA: 32

Education: B.S., Physics; M.A.T., Education; Ph.D., Astrogeophysics; R&D Management

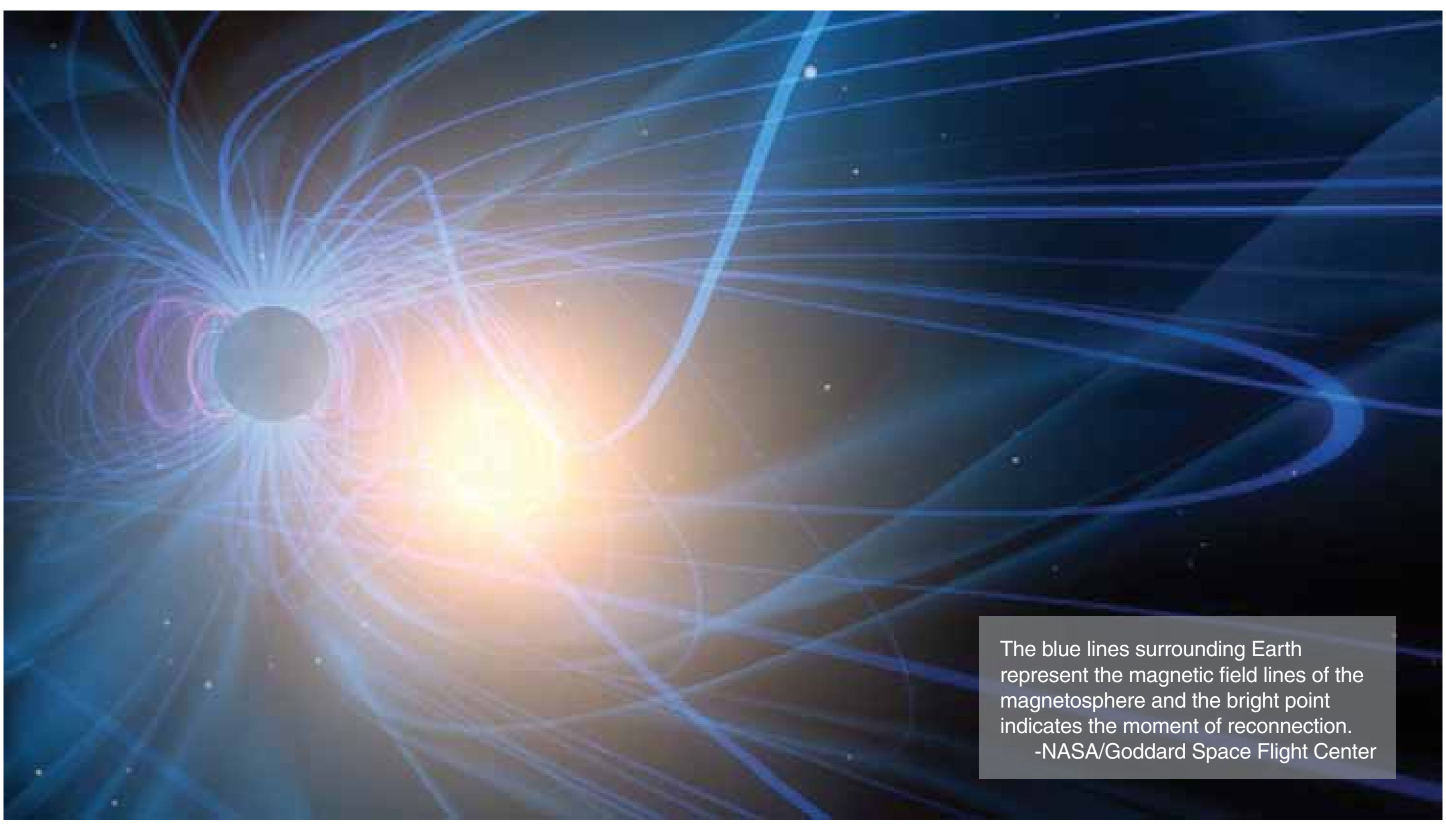
How did you become involved with MMS?

The initial opportunity was realized around 2000, when I jumped on the bandwagon with Jim Burch from SWRI [Southwest Research Institute]. Jim and I had collaborated before, and the idea behind MMS was already in study, so we decided to move forward and submit a proposal around 2003-2004. In 2005 we were selected for funding, and we received the official go-ahead in 2007. After a year of budget crunching and grinding, things really kicked off in 2008.

In terms of the science, I had been doing space plasma observations in graduate school at the University of Colorado, so this was a natural area of interest.

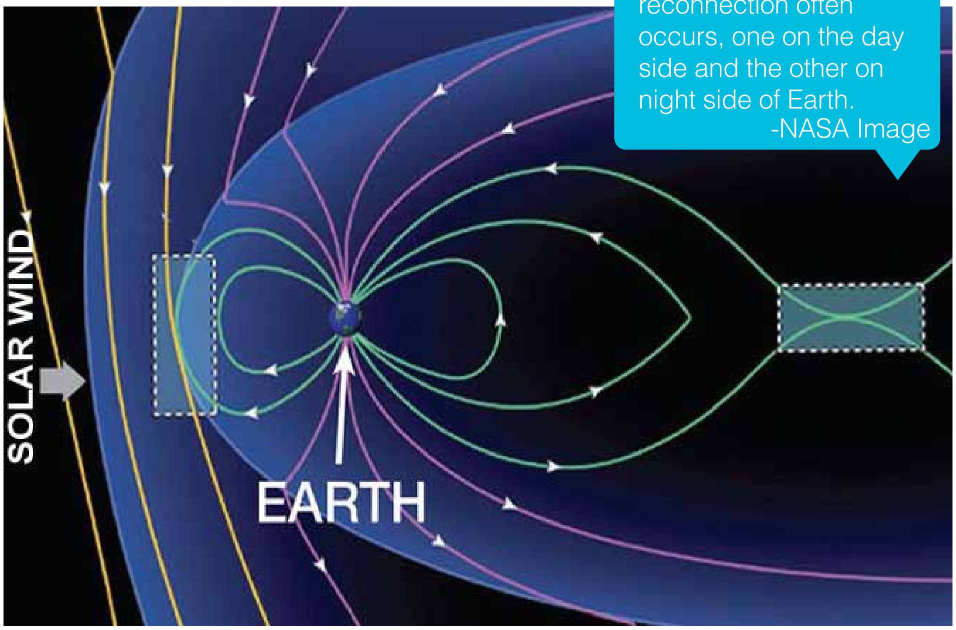
What are the particular science areas within MMS that are most exciting?

Again, these interests stretch all the way back to my graduate studies, where I was looking at plasma in terms of thermodynamics and kinetics. The scouring of material off of planets by solar and stellar winds is a key element to understanding the formation of an atmosphere, which is essential for life-support. Most energy from the sun comes to the surface of the earth as photons, but a lot ends up in the atmosphere by way of magnetic fields. This enables electromagnetic coupling, where plasma gas is carried in magnetic currents. Once such a connection is established by reconnection, a lot of energy is transmitted into the atmosphere—and it results from magnetic reconnection. When this energy is released over the earth at night it forms the Auroras, the result of energy heating up the ionosphere. Ionized material from the earth that is no longer trapped by gravity expands into space and couples with plasma from the sun during magnetic reconnection.



The blue lines surrounding Earth represent the magnetic field lines of the magnetosphere and the bright point indicates the moment of reconnection.
-NASA/Goddard Space Flight Center

MMS Mission Overview



MMS will use a two-phase orbit strategy to explore two different regions where magnetic reconnection often occurs, one on the day side and the other on night side of Earth.
-NASA Image

This process is important for understanding what happened to atmospheres on other earth-like planets such as Mars and Venus. Magnetism carries and transmits energy, impacting the stability and erosion of atmospheric gases. Mars lost an atmosphere and could have lost an ocean, and Venus is extremely desecrated, possibly from the removal of water by the solar wind. How atmospheres play with the sun and other stars can help explain what makes a stable atmosphere and ultimately, a habitable planet.

What innovations allow for MMS to capture this phenomenon of magnetic reconnection, and what challenges did the mission face implementing the necessary technology?

Let me answer that by explaining a little more about how reconnection works. If you think of two layers of energy flowing side by side, there is a cell boundary of current that separates them and keeps each layer distinct. In order for reconnection to occur, there needs to be a disturbance in the boundary, some kind of crack in the current sheet that weakens it enough to allow for the separate magnetic fields to connect through a pathway. A big part of the mystery here is what makes the current weaken? What makes the crack?

When the magnetic fields connect with each other, this reconnection feature makes a tail which is visible to us on earth as the Auroras. While humans have observed the Auroras for millennia, the exact details of the process causing magnetic reconnection have been left unexplained. We know it happens because our spacecraft have detected the reconnection zone before, but we have not been able to capture any serviceable data because it happens so fast. There is a necessity for fine-tuning in every respect; MMS is really the culmination of 20-30 years of work!

The thin layers of reconnection pass by in the blink of an eye, so the need for high-speed resolution was critical. MMS can capture plasma measurements 100x faster than previous missions, at 1/10th of a second. This was a major innovation, but also a major challenge. We solved one issue by placing sensors all over the spacecraft, but even producing that many sensors was a challenge, because we needed so many to get the right measurements. There was also the technical hurdle of designing the hot plasma composition analyzer, which was done at SWRI. They needed a radio-transmitter that could detune to hydrogen in order to pick up other elements accurately. So the instrumentation did not all come together without difficulty.

Another challenge dealt with the data itself. You can imagine with data being captured so quickly, it's being produced at a prodigious rate. With way too much data being captured by all four spacecraft, the question is how to send the good stuff? It's a bit like baseball; you have to wait through long periods for just a few flashes of action. We needed to develop the right tools and software for our scientists to not only figure out what to transmit, but also to be able to input back into the system so it gets smarter as time goes on and more data is collected. We only need a few percent of the total data, so what is the right percent and how can we identify the interesting intervals? We have the ability to watch everything in low resolution, but it's more important to maximize transmission of what we need to see in high resolution.

Finally, the Goddard designed and built Navigator system is crucial to the success of the mission. This was a major innovation in that the MMS spacecraft fly above the GPS satellites, and are able to still use that data to navigate. Spacecraft operations are handled by Goddard, and since the whole system was done in-house, it was satisfying to see such a challenge overcome by our own team.

What is the current status and timeline for the mission?

I'm happy to say that everything is working just beautifully so far. We made this thing complicated enough to worry a lot of people, but it's working great! We had our first encounter with the Holy Grail this past weekend [8/15]: the magnetopause, which is the thin layer that defines the boundaries and connections. There was a huge blast of solar wind and the spacecraft captured what we call flux-transfer events, little blips in the data that show the magneto-pause layer as reconnection occurs. To think of it visually, solar winds blow waves on the boundaries, disturbing them and somehow provoking reconnection. The data itself tends to be a little mind-numbing, but out of that comes a picture that takes a little imagination. And we use simulations to create imagery that can help people understand the mission.

Right now the spacecraft are in a six month orbital period in which they cross the magnetic field boundary on the day side (we call this upstream in the solar wind). After this period, the spacecraft spend the next six months on the night side. Then a second pass across the day side (one year from now); and finally, a second pass across the night side, during which the apogee of the spacecraft will be raised and they will travel farther into space to find the outer boundary edge where reconnection occurs. If you imagine the reconnection field like a rubber-band that snaps back, and in the process releases energy, we want to capture the details of what is happening, when it happens, and how fast it goes.

This process, however, is highly variable. We still don't know when and where reconnection will occur, or what turns it on and off. Why is it episodic? It is explosive on the night side (Auroras); but how does it decide when and where to occur? What controls how fast it goes? These are all questions we hope to answer with data from MMS. As they say, the devil is in the details….

A mission like this must take an extraordinary amount of effort from multiple parties. What major partnerships and collaborations have made MMS possible?

We definitely have had a good division of labor. SWRI has been our main contractor, and has sub-contracted with the University of Colorado to operate the instruments and run the data. On the science side, the University of New Hampshire is coordinating the electric and magnetic field measurements. The Johns Hopkins APL [Applied Physics Laboratory] handles the energetic particles. We also have international collaborations, in Sweden—working on electric fields and also the system that connects spacecraft in launch and deployment (provided by RUAG); and in Austria, where the spacecraft neutralizer—what keeps the craft from charging in sunlight—was made.

What applications and tech transfer opportunities might come out of MMS?

In many ways we designed the MMS mission to provide the research foundation for a space weather service like the National Weather Service. Space weather prediction is a major application because of how solar winds and these reconnection events can impact satellites, which in turn can cause all sorts of problems on the ground for GPS, telecommunications, etc. There is still a research and operations dichotomy, however, and MMS is very much a research mission. We talked about putting a real-time beacon on the spacecraft, so that data could be delivered to a user on the ground and used for monitoring, but budget considerations and resources dissuaded us. Again, we're still in a research phase, so the kind of operations that NOAA does for instance, in terms of weather prediction and monitoring, will be enabled by the MMS mission, but not directly part of it. We are trying to increase space weather consciousness so that in the future, agencies like NOAA and the DoD, along with businesses, can safeguard their space assets.

What has been most rewarding in your work with MMS?

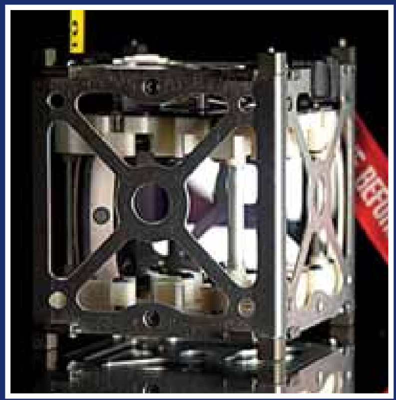
Seeing complicated systems work well together after years of collaboration and cooperation with all different parties is the most rewarding thing. After so many long meetings and teleconferences, so much coordination—across the country and overseas—to see it all come together…. It was a real hoot and holler when the first data arrived, a lot of congratulations. Of course, now we have to figure out what to make of it all! But that's also rewarding, because we do this to expand our knowledge and to learn from the data. Now we get to start thinking about what papers to write and what comes next.

COMMERCIALIZATION OPPORTUNITIES

Small Satellite Market

Alternatively called CubeSats, NanoSats, and microsatellites, SpaceWorks Enterprises estimates a 72% increase in launches in 2014 compared to 2013.[1] Furthermore, commercial ventures like SpaceX are investing heavily in this market, with significant growth anticipated in the coming years. Science applications, along with Earth observation and communications will drive this industry and present new opportunities for NASA Goddard technology.

You can read more about Goddard's activities in the Small Satellite arena in Tech Transfer News! See the Summer 2014 issue: http://itpo.gsfc.nasa.gov/news-events/publications/.



[1]SpaceWorks Enterprises, "2015 Small Satellite Market Observations:" http://www.spaceworksforecast.com/docs/SpaceWorks_Small_Satellite_Market_Observations_2015.pdf.

Innovation Insights

Instruments on the MMS spacecraft are tasked with measuring electric and magnetic fields, fast plasma, energetic particles, and hot plasma composition of the Earth's magnetosphere. For the first time, scientists will have data that will help explain the phenomenon of magnetic reconnection in the electron diffusion region, which will lead to a better understanding of the dynamics and processes of space weather. The effects of space weather threaten operations of satellites and other space assets orbiting the Earth, which is a growing market for telecommunications, GPS, Earth observations, and defense.

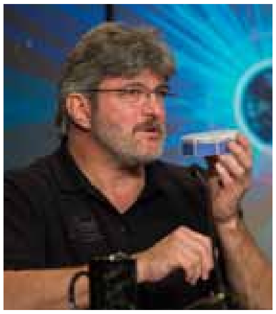
In order for the MMS Mission to be successful, there was a suite of instrumentation that not only had to be developed and assembled, but had to be done exactly the same on all four spacecraft. One of the challenges facing the MMS team was the ability to manage thermal performance. In order to do so, a novel Optical Bench Assembly (OBA) was designed to ensure operating temperature limits on the spacecraft (GSC-17127-1). The temperature limit of some of the instruments is lower than the average temperature of the spacecraft, so it is critical that heat transfer is managed and that the instruments are conductively isolated and radiatively insulated from the spacecraft. The Optical Bench Assembly instruments provide navigation for orbit raising and attitude maneuvers. There are a number of companies involved in the production of OBAs, including Vanguard Space Technologies, Alliance Spacesystems, and Alliant Techsystems.

In addition to the Optical Bench Assembly technology, there was a host of other innovations pertaining to the stringent flight requirements of the mission. NASA Goddard GSC-16471-1 describes the MMS Spacecraft Flight Software, which consists of command, data handling, and attitude control. Along with spacecraft commanding and telemetry, the software also performs attitude determination and control. A key component of the software system is the communication between ground and spacecraft operations. The ground system can send commands to the spacecraft, which will then carry out configuration changes to the onboard software and/or hardware. Command handling and routing, telemetry handling and routing, attitude determination and control, File Delivery Protocol, and custom interfaces management are all features and benefits of the Spacecraft Flight Software.

Interviews with Craig Tooley (MMS Project Manager) and Brent Robertson (MMS Deputy Project Manager) will discuss the project and some key innovations that are already making MMS successful. You will read about some of the issues involved with managing the flight requirements and data collection of the mission; and you will also receive some insights into the many partnerships and collaborations that contributed to the MMS Mission. Central to the mission is a collaboration with Southwest Research Institute (SWRI), the primary contractor hired by Goddard to work on the science instrumentation and data. This central partnership will be discussed in many of the interviews, and symbolizes the integration of science, engineering, and project management that such a large-scale mission requires.

You will also learn of the MMS Navigator, an innovation that has already attracted commercial interest and corresponds to flight dynamics and operations. We will hear more about the Navigator in proceeding sections, and will also talk to some of the Goddard scientists and engineers who made this mission possible.

Craig Tooley
MMS Project Manager



Code: 461

Years with NASA: 32

Education: BS, Mechanical Engineering; MS Mechanical Engineering

How did you become involved with MMS, and what are your primary duties as Project Manager?

I was assigned to take over in June of 2011, shortly after the completion of the design review. I was brought in at that juncture, because the team was beginning to have flight subsystems built and plans for integration were getting serious. I was brought in at this later stage because of my experience managing in-house spacecraft missions such as the LRO [Lunar Reconnaissance Orbiter]. I had experience leading teams with in-house builds, and was very comfortable working with engineers and scientists to build and integrate systems.

My role is ultimately to lead the team and manage everything up through launch and commission, making sure we surmount any and all challenges. This not only means building on time and on budget, but fostering a real esprit de corps to perform successfully.

What particular challenges helped define MMS?

We started with a challenge never done before: to simultaneously build four of the exact same spacecraft—four of the same observatories together at one time. There are over 100 instruments, which makes the project both logistically and technically complex. The big challenge to build the spacecraft simultaneously was foreseen, but what was unforeseen were problems with some of the electronic parts, especially the Fast Plasma Instrument (FPI), which really threatened the viability of the mission.

A prototype of the dual electron spectrometer being built in a clean room at Goddard Space Flight Center in Greenbelt, Md.
-NASA/Karen C. Fox

Late in the game we had to retest all of the observatories in a vacuum lab at the Naval Research Lab, which meant transporting all of the spacecraft to their facility. We had planned to do it at Goddard, but when the time came, we couldn't use the lab because it was already booked. Anytime you have to ship spacecraft it's logistically challenging, and we were dealing with everything times four. Then we had the government shutdown, which put our funding and schedule in jeopardy. The question becomes how do you get the team to recover from a full halt?

But despite all of the challenges, everything came together on budget and on schedule, and we are very proud of that. There was a lot of concern at many levels of NASA management that we weren't going to be able to build all four spacecraft together on time and budget.

What is the current status of the mission?

As of today (we launched back on March 12th), we're only 7-8 days away from finishing the commissioning phase [on Sept. 1]. After launch, the first thing we do is test the spacecraft without instruments. Then we begin to commission all of the instruments—calibrating, checking them out, making final adjustments and software uploads. Finally, the full science and operations phase starts on September 1st. Once we're done commissioning the spacecraft, off they go to the scientists.

Everything right now is on schedule. With 100 instruments—and they're not all different, but it still takes quite a bit of orchestration—the commissioning and flying in formation with everything unfolded, there was a lot of accomplishments in this current phase. And as I've said, everything is working very, very well. Such a complex array of spacecraft, instruments, and operations working together is a testament to the ability of the team. It all went according to schedule as planned (even if there were some things that didn't go as planned along the way…).

What partnerships and collaborations contributed to the mission's early success?

Our principle partner all along as has been SWRI, which was competitively selected by NASA to build the instrument suite. They subsequently partnered with a number of institutions. SWRI is a non-profit, but private institution in San Antonio, TX. Goddard was responsible for the spacecraft and mission operations, but most of the science is run through SWRI and their sub-contractors.

There is a long list of contributors: the University of New Hampshire, University of Colorado, Johns Hopkins APL [Applied Physics Laboratory], a company called Meisei from Japan who built some components, the IWF space agency in Austria, the space agency in Sweden, the Marshall Space Flight Center (who handled some testing); not to mention another long list of industrial partners for additional parts and components. Luckily, SWRI brought in a lot of these partners, so direct coordination from my vantage was not so demanding. I did have previous experience getting equipment from national and international institutions on other missions, so that certainly helped when I was needed to facilitate and coordinate among various parties.

MMS rollout to the pad prior to launch.
-NASA

Can you talk about the objectives of MMS from an applications and tech transfer perspective?

First off, the primary purpose of the mission, our goals and objectives, were purely scientific. We did not have any specific objectives for commercialization, other than the general push to commercialize NASA technology. But even though MMS is a research mission, we did have a very good example of a successful commercialization of technology in the Goddard-built Navigator system. The Navigator was designed and built entirely in-house—and MMS is the first mission to use it. The ability to navigate and control all four spacecraft together in precise formation was fundamental to our success.

The Navigator technology has already been licensed and commercialized. Basically, the primary innovation is to use GPS data much higher than ever before. MMS flies farther out than the GPS satellites; our spacecraft are looking down at them, and GPS is not designed to work with anything above it. So we designed a system that can pick up weak, weak signals from above and use them for precise positioning. We have achieved precision within 100 meters in space! This is the first time spacecraft have been flown so far above using GPS, and this technology will have a lot of viability in future missions, along with other commercial applications.

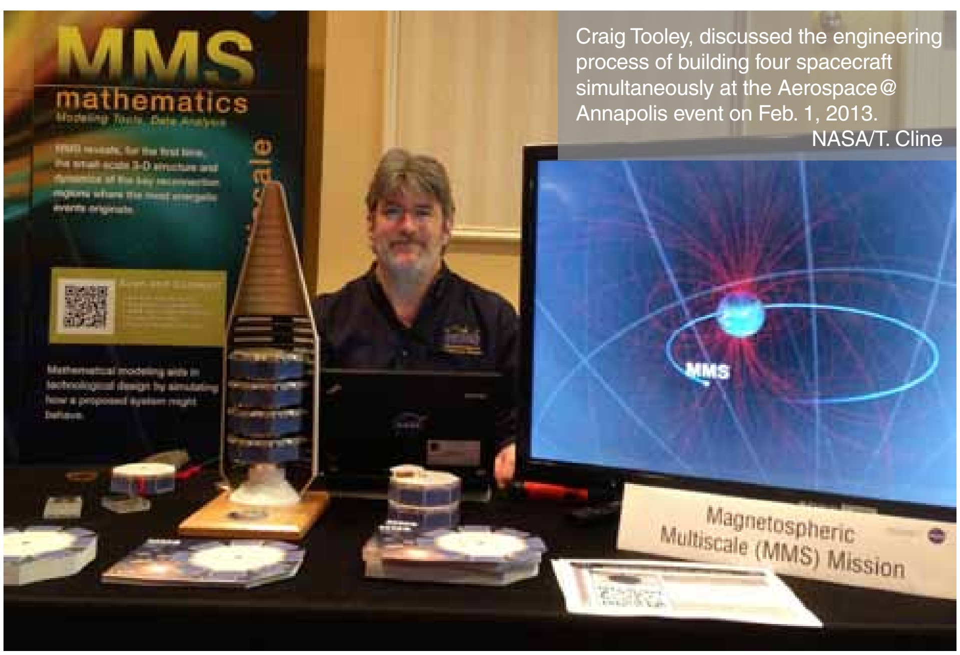
What kind of public outreach have you and your team done for MMS; and what happens now that you get ready to hand off the mission to operations?

We have a dedicated person for public outreach, Troy Cline, who does everything from help us make videos about the mission to working with teachers to develop activities in schools. There are over a dozen managers and engineers that are regularly active on the speaking circuit, and this has become a common part of our missions, a role we all embrace. We know that we're spending your tax dollars, so we are invested in how we can explain our work to the public.

Once commissioning is complete, which is the last part of the development phase, I formally pass control to Space Science Operations. The engineers and those who designed and built the spacecraft stay on call in case problems arise, but September 1st signals a new phase of the mission. MMS is certainly not routine, however, because we are using new flying formations and trying to capture previously unknown data, so many of us stay on in supporting roles. We want to keep the public as involved as possible through all stages of the mission.

What has been most rewarding in your work with MMS?

Well, when all four spacecraft successfully separated and we watched them operate on their own on the telemetry screen—that is a highlight on any mission, and we had that highlight times four! All of this human effort converging successfully…that is really a crowning moment. It's amazing to me that over 300 people, working across the country and the world in a symphony together, got it all right. It doesn't take much to make a mission like this fail, and it's incredible that it all works beautifully, the symphony playing the perfect notes. All this technology is still built by people; and nobody ever built these four spacecraft before, let alone four of the same spacecraft at the same time. And you don't get to send them up for a test drive and pull them back to fix….



Craig Tooley, discussed the engineering process of building four spacecraft simultaneously at the Aerospace@ Annapolis event on Feb. 1, 2013.
NASA/T. Cline

COMMERCIALIZATION OPPORTUNITIES

Military Global Navigation Satellite Systems

As military operations rely increasingly on technology to take soldiers out of harm's way, automated weapons systems need sophisticated navigation for missile and artillery guidance. A 2014 Frost & Sullivan report found the Military Global Navigation Satellite Systems market earned revenues of $1.98 billion in 2013, and estimates that number to reach $2.18 billion by 2022. The study also identifies North America as the biggest market, while Central Asia, Asia Pacific, and the Middle East are the fastest growing.[2]

With an increase of satellites that serve military operations, the MMS Mission will produce valuable data related to space weather that can serve markets such as this one looking for improved predictive models as a means of protecting assets and investments.

[2]Defense-aerospace.com, "Need for Precision Strike Capabilities Fuels Military Global Navigation Satellite Systems Market:" http://www.defense-aerospace.com/articles-view/release/3/153400/need-for-precision-strike-fuels-global-navsat-market.html.

Brent P. Robertson
MMS Deputy Project Manager

Code: 461

Years with NASA: 21

Education: MS Aerospace Engineering

How would you describe your day-to-day responsibilities as MMS deputy project manager?

Working with Craig [Craig Tooley, Project Manager] has been great. We divvie up some of the responsibilities, but also serve as fill-in for each other. I tended to concentrate more on the schedule and interrelated deliverables. My job as deputy was to figure out how best to complement Craig. As we move from design to development to test to flight—basically our jobs are winding down. We serve as mission directors for the next 5.5 month commissioning phase and then turn it over to operations. We peaked at over 350 people, less than half that many are working on it now. It's bittersweet…like seeing a kid go off to college.

Can you talk a little about the mission after the successful launch?

We need to see the process of magnetic reconnection in three dimensions, taking measurements in multiple dimensions. To do the science we want to do, we have to fly four spacecraft with multiple measurements from each. Briefly, magnetic reconnection is a universal process that occurs in planet formation, black hole accretion disks, solar coronal mass ejections, and limits performance here on Earth in fusion reactors. It's not very well understood. MMS flies through the Earth's magnetosphere which is the best place to study. It occurs on such as small scale in fusion reactors that you can't really study it there. Other missions have observed it, but not in enough detail to help understand it. With our four satellites and 100 instruments, we will take magnetic and electric field measurements while it occurs.

Engineers work on one of four Magnetospheric Multiscale (MMS) spacecraft in a cleanroom at the Naval Research Lab, Monday, August 4, 2014, in Washington.
-NASA/Bill Ingalls

At ITPO we're interested in innovation and partnership. Two innovations stand out: 100x improvement in speed of measuring fields and formation-flying four spacecraft for 3D measurements. Can you talk a bit about each of those?

To accomplish the science, we fly through magnetic reconnection events very quickly—it's not stationary, it's moving as well—and we can fly through it in less than a second. So we take measurements at up to about 1000 times per second. I wouldn't say that's new technology, but it's what's required. We store that data but can't downlink it in real-time. We have an innovative process where certain events will cause a trigger indicating significant data has been taken, and we have a scientist in the loop who can override the spacecraft software and decide which data to downlink. Probably John Stone at SWRI.

We have a number of innovations flying four satellites as close as 10KM. The reconnection events happen in a small region, on the order of 10KM. The scientists determine the best separation. We're starting with 100KM and will gradually get closer as the scientists work to determine an optimal separation. What enables us to do that include precise determination of where we are in the orbit. We use a Goddard-developed navigation system that receives GPS signals from above the constellation—we are the highest altitude spacecraft receiving GPS signals. We're thrilled with the performance; we know our position to within five meters, and we're about 1/4 of the way to the moon! Our formation flies four separate, but very similar, orbits. We have on-board propulsion, controlled by our flight dynamics folks on the ground. This is all enabled by our Navigator, flight dynamics, and high-precision thruster maneuvers with a precision accelerometer process running in a closed loop.

Are there any other innovations that help MMS stand out?

Because we're measuring magnetic and electric fields, we had to build a spacecraft that's very electrostatic ally and magnetically clean, which will serve us well for future missions. GSFC has never built any spacecraft that are so clean. We have booms to get sensors further from the spacecraft. Very stringent requirements: less than 10 nano-tesla on some sensors. Difficult to achieve. Some materials were prohibited. We designed the electronics to minimize current loops, electric field and magnetic moment. We had to test at the board and component level to make sure no charge was collecting. Also, a lot of time was spent degaussing equipment. It was quite an effort to produce a clean magnetic and electrostatic observatory; it required a combination of materials selection, design process and testing.

One instrument—the hot plasma composition analyzer, built by SWRI—is first of its kind. Mass spectrometers have been flown before, but in this region we'd be swamped by hydrogen ions; this instrument was developed to filter those out and allow detection of other ions. We haven't turned those instruments on yet. It's an area where we are definitely pushing the technology.

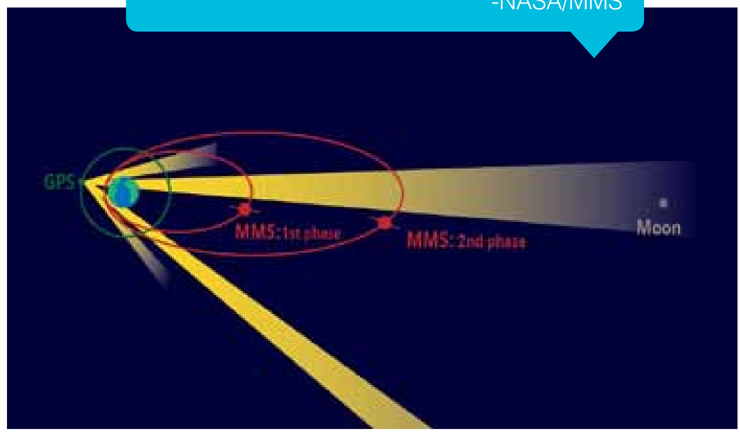
We have wire booms that run up to 120 feet across. We take up the footprint of a baseball field with them fully deployed and spinning at three RPM. We have a total of 44 boom deployments, started over the last couple of days, and so far everything looks good. The booms were built by the University of New Hampshire. UNH did an excellent job under tight time constraints. We're looking forward to deploying them.

Can you talk more about the partnership with SWRI and other collaborations?

SWRI provided the instrument suite for MMS and the science leadership, including the PI, and the science operation center. While ops are out of Goddard, science is being done at LASP. Instruments were delivered from all over the U.S. and in some cases internationally. SWRI was the lead contractor to acquire the instruments, create the suite and deliver that to us. They'll perform science ops over the next two years.

I see many universities we work with providing hardware for future missions, probably science rather than commercial. MMS has contributed to advancing the state of the art in instrument building. We have 100 instruments between the four spacecraft, built by universities, SWRI, APL and Goddard. That capability will serve future missions well.

The red ellipses show the MMS orbit paths. Each spacecraft uses GPS signals – which come from satellites situated along the green circle shown surrounding Earth–from the far side of Earth to track its position.
-NASA/MMS



We understand that results are expected before this issue will come out. Anything particular to look for, and any major events to note?

We recently turned on the fields suite, deployed our axial double probe receiving elements, and magnetometer booms—everything is going to plan. We have a 5.5 month commissioning process. We should be in formation by July. Everything is nominal or better so far; navigation is actually more accurate than we expected, at our apogee. We're thrilled with that performance.

Our mission carries a 5.5 month commissioning, plus two-year science ops. There's enough fuel to extend another year depending on funding.

What's the biggest challenge you've faced on MMS?

We overcame a huge challenge in parts. We use opto-couplers on some instruments, and in screening them we found some were failing. We're pushing the state of the art on those. Getting them in quantity—we're flying over 300 of one particular opto-coupler—from a supplier who was used to delivering them in much smaller quantities was difficult. Just the logistics of building four spacecraft at once was quite something, building all the boxes to put on the four observatories, integrating them and testing them. There was a lot of concern about whether we could do this on time and on budget. It was a lot of work, shuffling things around and swapping components to keep integration moving along.

Innovation Corner

The flight dynamics of the MMS Mission were uniquely challenging, considering this was NASA's first ever mission to fly four spacecraft simultaneously in formation. In order to collect data from the thin but 3D space of the electron diffusion area, the spacecraft will fly in formation using broadly tetrahedral forms. Before we can address that challenge, however, we must take a look at an innovative solution to launch the spacecraft in proper orbital position, another extremely sensitive operation.

Due to the multiple factors determining optimal orbital and flight patterns, a sophisticated analytic tool was needed to plan the precise launch window for MMS. The SWM76 Launch Window Analysis Tool for Magnetospheric Multiscale Mission (GSC-17339-1) enabled the MMS team to correctly identify the exact conditions and parameters for launch. A paper by Trevor Williams (Aerospace Engineer, NASA Goddard) outlines the problems facing the MMS launch and the development of SWM76 to address the many constraints governing the MMS orbit.

In "Launch Window Analysis for the Magnetospheric Multiscale Mission," Williams explains the function of the SWM76 tool, highlighting the Goddard-designed solution for complex launch constraints. This technology will clearly be useful for future missions, and also has commercial potential in the growing market of space assets. Not only does the SWM76 excel in analytic efficiency, but it also produces graphical results that helped the MMS team evaluate which launch windows would be most impacted by the various mission requirements, and how best to predict the most successful launch opportunity. To give you a sense of how fast the tool is, the SWM76 can scan 32,761 different launch orbits to be carried out for a specific launch day in less than 10 seconds; in contrast, a traditional orbital simulation would take 8 hours to test a single one of those orbits.

Data analytics are big business in the commercial sector, and they are also a big deal at NASA Goddard. Big Data technologies developed in-house have helped countless missions, and are actively being explored in tech transfer and commercialization opportunities outside of Goddard Space Flight Center. We will talk more in the next section about data handling and processing on the MMS Mission, but before we do, it is worth taking a step back to see how systems automation plays a role in making sure MMS accomplishes its goals.

As budgets are stretched thinner and thinner, automation of all routine operations is an excellent means of cutting costs and saving both time and energy in the command center. This frees up operations personnel to focus on other tasks, while they also remain available to handle any systems anomalies and necessary configurations. Previous missions have automated several key functions, but the MMS team is developing a way to solve "closed-loop" automation across all shifts. By using mostly legacy software, the Closed-Loop Automated Ground Data System for Support of the MMS Constellations (GSC-14476-1), can dramatically improve mission operations through software architecture that does not require building a system from scratch. Such a comprehensive systems automation could have substantial benefits for future missions, and have commercialization potential for applications that have yet to integrate multiple systems with a single closed-loop solution.

Roberto M. Alemán
MMS Observatory Manager

Code: 461

Years with NASA: 28

Education: BS, Electrical Engineering and Biology

How did you come to NASA Goddard; and what projects have you worked on before MMS?

The reason I came to Goddard from college was that I initially went to Patuxent River Naval Air Station and did reliability maintainability for the FAA, but it wasn't challenging. I had an opportunity to come to GSFC, knocked on the doors and stayed.

I spent 11 years on ESA METOP and Eumetsat. We provided six instruments, five from the U.S. and one from Canada. Two of three METOP satellites are on orbit, and the third is to launch this year. I will be NASA's METOP mission manager. We will again provide instruments to the Europeans.

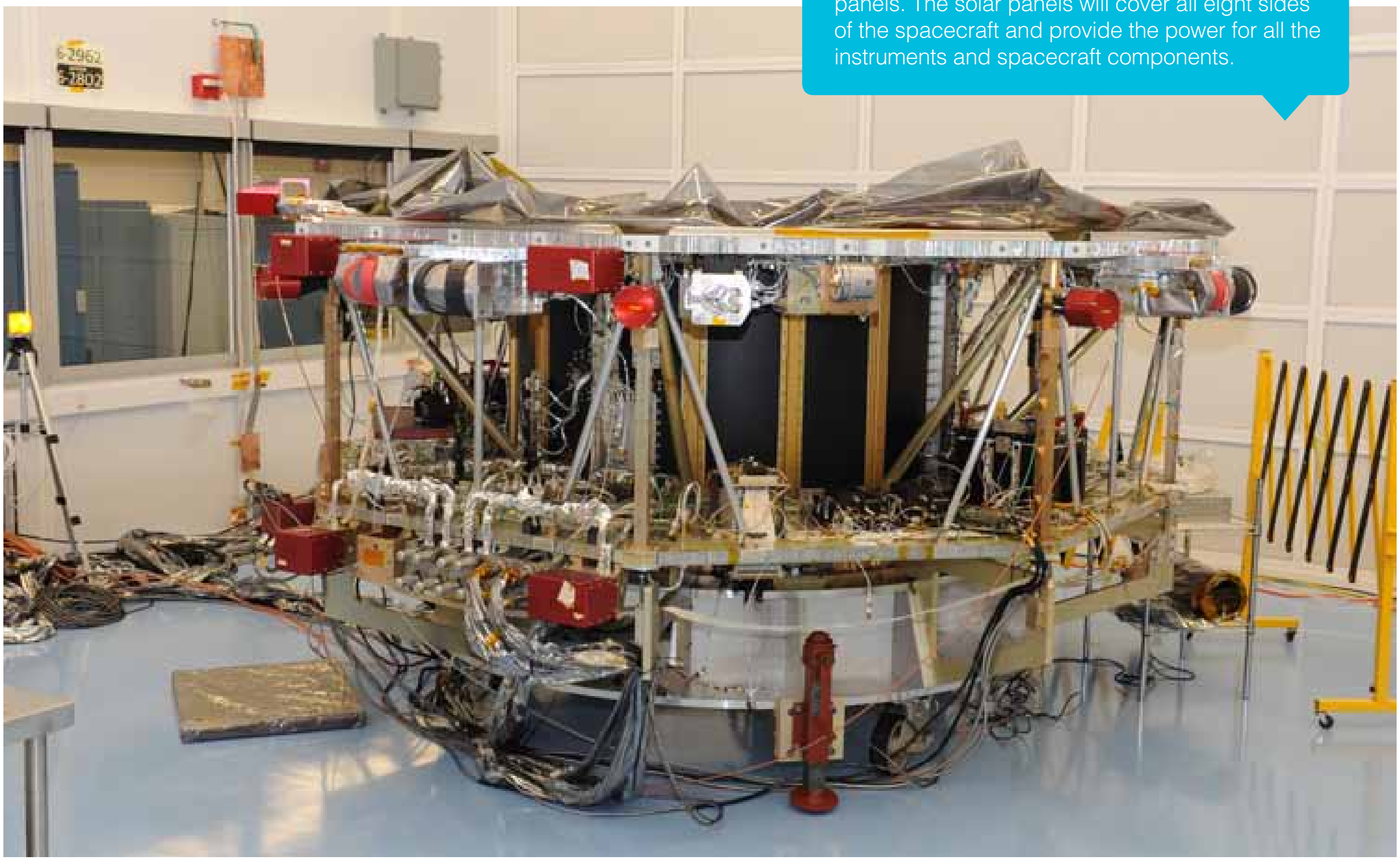
What is your role as Observatory Manager?

I was in charge of the team of lead engineers on the various disciplines: RF, contamination, navigation, mechanical, thermal, etc. Overall, I'm in charge of providing the pieces while the Integration Manager put them together. For the past seven years I was in charge of seeing that everyone on the team worked together, and had what they needed to do the job without interruption. With the spacecraft on orbit, my job is basically complete—just closing out a few contracts. Systems engineering will probably run through the end of the year.

A Thermal Technician finalizes the thermal taping on the baffles prior to bake-out.

Innovation Corner

After installing two deployable boom electric field sensors in the thrust tube and attaching the long boom with the magnetic filed sensors attached, the only thing left to be added is an array of solar panels. The solar panels will cover all eight sides of the spacecraft and provide the power for all the instruments and spacecraft components.



Innovations we've identified for the MMS mission include formation-flying multiple spacecraft, high rate electromagnetic sensing, multi-spacecraft orbital analysis, high-altitude GPS navigation and building four spacecraft simultaneously. Is there anything you'd care to add?

The solar arrays were specially designed to make sure that everything was grounded and the cells did not create any islands of charge, which required a special grid over the cells. The magnetic signature of the spacecraft had to be ridiculously low, and any buildup of static kept to a minimum. So far the measurements we've got in orbit show a magnetic field even lower than expected.

The major partnership on MMS seems to be with SWRI. Any others you'd like to mention?

Within that you also have University of New Hampshire, which is a major contributor with science and instruments, and University of Colorado, which has the science operations center—they will control the instruments once everything is up and running. When that will happen depends on how long it takes to deploy the spin probes, which is a slow process. I would guess 5-6 months.

What was your biggest challenge on MMS?

Having enough manpower and facilities; facilities was the biggest problem with JWST [James Webb Space Telescope] going on here at Goddard at the same time. We couldn't get the floor space to build four observatories, and the biggest thermal chamber was being used for JWST. We built our own clean room in a warehouse, and found a thermal vacuum chamber at NRL. The trouble was they didn't have a clean room, so we built another clean room in front of their chamber. As a result, NRL now gets to keep a clean room!

Manpower wide, just having to build four spacecraft at the same time was a big challenge for all the subsystems people—getting one navigator to INT while the second was in thermal testing, third on the bench and fourth being assembled. On the other hand, it worked to our advantage, because if we had a problem on one bird, we had others to work on, so there was no downtime. But it definitely was draining on everyone.

Can you think of anything else that is worthy of note on MMS?

If not the biggest, this is one of the biggest efforts Goddard has done: four big observatories, 4 x 12 feet, all at once. We hope that we will get another job that can exploit the skilled Goddard work force. MMS definitely had the "A" team in many ways. We got outstanding support from the administration at both Goddard and HQ. Lots of cooperation from the Applied Physics Lab at JHU [Jonhs Hopkins]; we used their facilities for vibration testing on GPS and RF antennas, EMI testing. Whenever we got stuck at this end for lack of facilities, they responded—almost without prior knowledge.

Dr. Conrad Schiff, PhD

MMS Flight Dynamics Lead

Code: 595

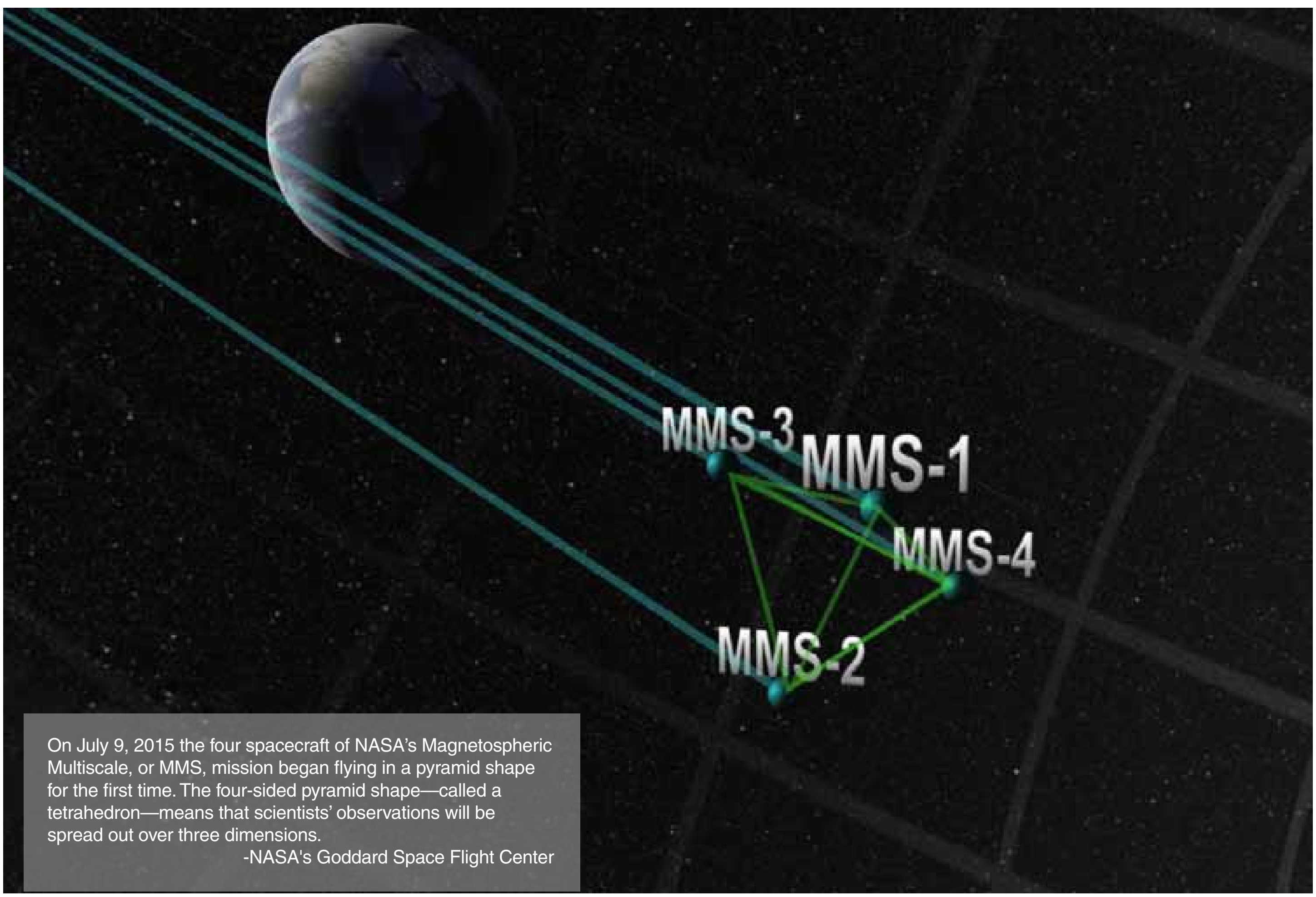
Years with NASA: 9

Education: Ph.D., Physics

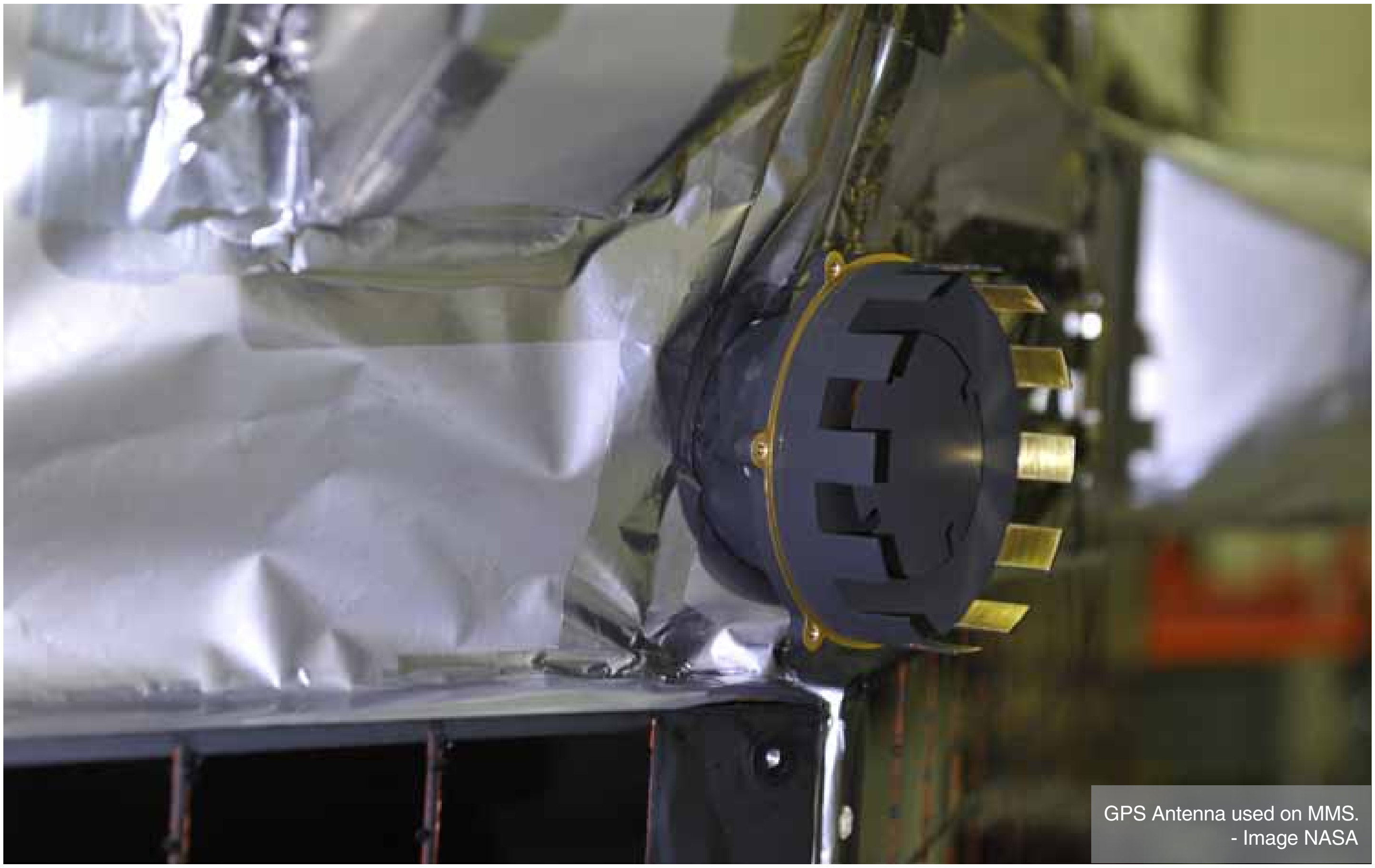
Can you give us a brief introduction to how you came to NASA Goddard and your work before MMS?

I was a grad student at Carnegie-Mellon in the PhD program and had a falling out with my adviser. I decided to get a job and started at Computer Sciences Corp. as a contractor, doing gravitational and orbital analysis. It's been a love affair ever since. I became friends with people in 595, and learned about an opening.

The high points since being at Goddard include being one of the lead designers on Clementine, the joint Goddard/NRL lunar mission. I did a lot of trajectory design for elliptical orbits and lunar insertion, and work leaving the moon for a planned rendezvous that didn't come off because the spacecraft died. I was also involved with ACE, which was a mission to L1, and lead trajectory on WMAP mission to L2. I've been on and off MMS since 1998 in one way or another; even before coming to the government I was flight dynamics lead for JWST. I will confess that after 5 years on MMS I do need a vacation!



On July 9, 2015 the four spacecraft of NASA's Magnetospheric Multiscale, or MMS, mission began flying in a pyramid shape for the first time. The four-sided pyramid shape—called a tetrahedron—means that scientists' observations will be spread out over three dimensions.
-NASA's Goddard Space Flight Center


GPS Antenna used on MMS.
- Image NASA

Can you talk about some of the innovations and accomplishments associated with MMS?

One major accomplishment is the operations center I'm sitting in now, a full-fledged soup-to-nuts system for flight dynamics: orbit determination, maneuver planning, and orientation. Each spacecraft has 20 instruments plus guidance and control equipment. We are tasked with flying the spacecraft in formation. We have a meta-instrument and are tasked to make sure the spacecraft are in position and orientation to get the science data. We interact closely with the science community, specifically SWRI, which will control individual instruments; but we will continue to control the formation in such a fashion that quality science measurements can be made across the fleet. We also deliver products that allow scientists to know with precision where each spacecraft was at a particular point in time, how fast it was moving and where it was pointed. My ground system team determines how each spacecraft is pointed—in the spin axis and phase—throughout the life of the mission.

A key innovation that helped us get off the ground is the SWM76 launch window analysis tool [GSC-17339-1]. The way to think about formation flying is that there's a queen bee and drones who fly about her. For MMS, we have baseline orbit for an imaginary spacecraft in the center of the tetrahedron. What we decided is that we didn't have to have exact fidelity on where each of the drones are. With SWM76 we can quickly determine which orbits look feasible, and then spot-check with high fidelity code. SWM76 uses classical methods with some nice tweaks to model the sun and the moon. It allowed us to calculate launch windows quickly - and was instrumental in recalculating our launch window after the government shutdown. We originally planned to launch in November. Thanks to MMS we were able to relax some requirements, test what-if scenarios, and check with the scientific community to find an acceptable launch window.


Assembly of one of 18 flight GPS Antenna.

I'd like to se SWM76 become a fully modular program available to anyone conceiving of a mission around the Earth. It has limitations

- it won't handle a lunar flyby or mission to the Lagrant points. I'd estimate that SWM76 saved literally millions of dollars by opening an early launch window.

Other innovations we've identified for the MMS mission include high rate electromagnetic sensing, multi-spacecraft orbital analysis, high-altitude GPS navigation and building four spacecraft simultaneously. Is there anything you'd care to add?

There was a very strong joint effort between flight dynamics and the navigator team on GEONS [Goddard Enhanced On-Board Navigation System]. We performed perigee-raising maneuvers just recently, and were able to get input from GEONS in a matter of minutes. That hasn't been available on earlier missions; you had to wait for tracking data. Immediate insight into what a maneuver actually did, 70,000 km away, is amazing!

My mission designers have done amazing work to coordinate maneuvers—40 so far, out of about a thousand we will do in the life of the mission, The work my team has done, flying four spacecraft in formation...I look around this room and see a lot of amazing people doing amazing things.

The major partnership on MMS seems to be with SWRI. Any others we should be aware of?

Spacecraft construction has been in-house. Jim Burch at SWRI is the PI. They contract out to LASP at UC Boulder. I'd like to give a particular shout-out to United Launch Alliance and KSC. They allowed us to work with them early because of the four spacecraft, which allowed us to tailor our software, the centaur upper stage which is still up and has to come down in a safe way.

The 'garden weasel,' an S-band communications antenna developed at Goddard.
-Adán Rodríguez-Arroy/NASA

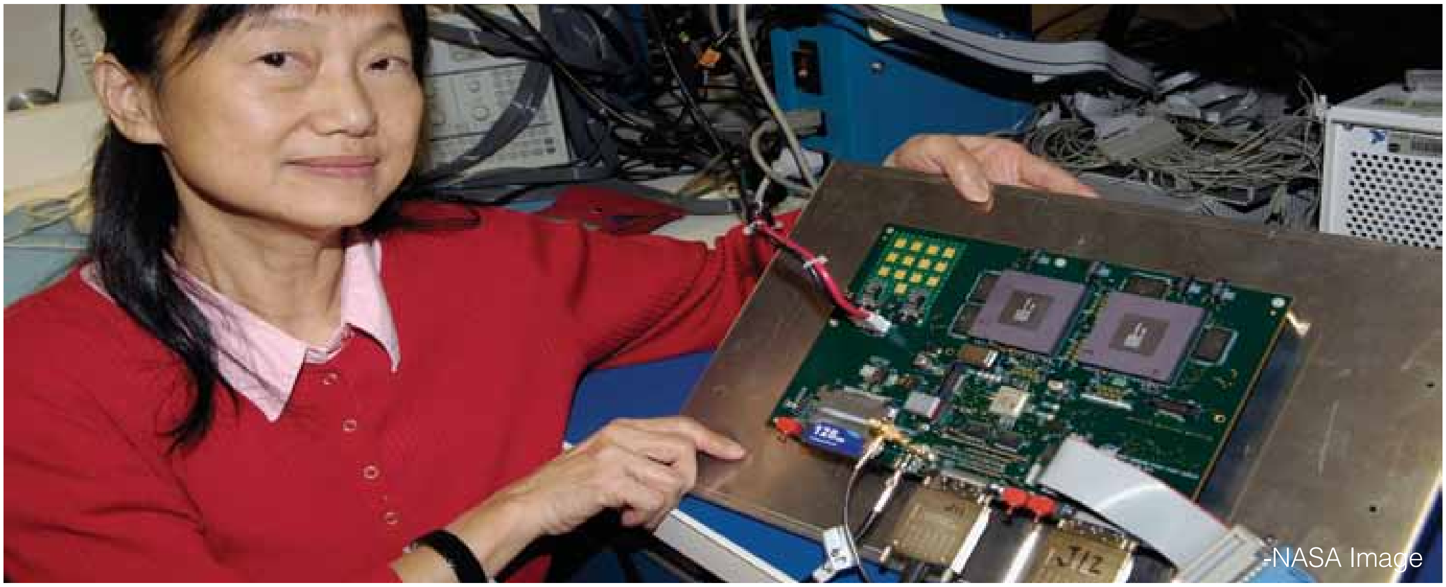
COMMERCIALIZATION OPPORTUNITIES

Earth Observation Market

According to a press release on Reuters.com, the Global Satellite-based Earth Observation market will grow at a CAGR of 11.34% during 2013-2018, with an estimated 258 Earth observation satellites launched from 2014-2029.[3] While this market will share some space with Small Satellites, the strong growth rate points to the importance of observation data for multiple applications, ranging from agriculture to defense, and resource management to natural disaster relief. NASA Goddard is already a leader in the field of Earth Observation, and the data collected during the MMS Mission will help develop better predictive models for space weather that threatens satellites and space assets.

[3]Reuters.com, "Research and Markets: Global Satellite-based Earth Observation Market 2014-2018 with Astrium, DigitalGlobe, DMC International Imaging & MacDonald, Dettwiler & Associates Dominating:" http://www.reuters.com/article/2014/04/17/research-and-markets-idUSnBw176036a+100+BSW20140417.

Key Technologies



One of the most exciting technologies of the MMS Mission is the GPS Navigator system. NASA Goddard has been working with GPS navigation since the early 1990's, but the MMS spacecraft have unique innovation that allows them to fly above GPS satellites and use very weak signals to achieve remarkably precise formation. As mentioned earlier, a novel tetrahedral flight formation was developed to capture the extremely thin but 3D space of the electron diffusion region (EDR). In order to accomplish this positioning, accurate navigation to the meter was demonstrated through the use of GPS-based technology.

The Goddard Enhanced On-Board Navigation System (GEONS) uses GPS satellites in a manner never before demonstrated. With just a slight signal received in orbit far above the satellites, the MMS spacecraft can navigate into the optimal formation to capture data in the EDR. While pre-launch simulations estimated the spacecraft would detect 2-3 GPS satellites, MMS is already picking up 9-12. This innovation will enable future missions to take advantage of enhanced navigation without costly development.

The Navigator technology has already been commercialized, licensed to Broad Reach Engineering, in addition to a number of other companies through successful programs like SBIR. There are also opportunities in the growing CubeSat and NanoSat market, which is always looking for ways to cut costs and make cheaper satellites for a range of commercial and governmental applications. Designed and executed entirely in-house, this technology is a great source of pride for the MMS team and NASA Goddard.

Once the MMS spacecraft are in position to collect data, the real work begins. With capturing speeds on overdrive, the sheer amount of data collected by the instrument suites is a massive challenge in itself. The MMS team needed to develop solutions not only to handle the data, but also to process it as much as possible before transmission, in order to conserve power and help the ground team find efficiencies in its research objectives. New software technologies contribute to the back-end success of the mission, helping MMS scientists generate the most productive results possible.

MMS-specific software applications were developed to facilitate magnetometer data. A MMS Magnetometer Data Processing and Preliminary Calibration Software (GSC-17353-1) uses an innovative calibration format to produce, update, and exchange data between the various institutions collaborating on the MMS Mission. The software runs autonomously and the calibration algorithms are specially adapted for use on slow-spinning spacecraft, providing magnetic field data in a timely manner to support various aspects of MMS operations. While current use is limited to the subset of MMS data users, there is potential for future re-engineering for other NASA missions. Furthermore, the development of such a technology is a true collaborative effort, demonstrating Goddard's ability to incorporate multiple institutions into a single mission.

Before the data produced by the MMS Mission are sent to the ground, the Command and Data Handling subsystem (GSC-17223-1) provides the computing power necessary to execute stored or uplinked commands and distribute those commands to the Instrument Suite (IS) and other spacecraft components. This subsystem is tasked with spacecraft command and telemetry, time management and distribution, analog data acquisition, and interfacing with the IS and other hardware components. There is also a built-in redundancy feature to ensure spacecraft operations and mission integrity.

Finally, a new compression algorithm based on an advanced Discrete Cosine Transform predictive coder is being developed by Goddard to increase the lossless data compression ratios of natural, high resolution, color, or gray-scale images (GSC-17237-1). By compressing UV, visible, IR, and multispectral space science images, the Discrete Cosine Transform Minimum Mean Square Error Predictive Coder (DMPC) can improve data throughput from MMS instruments. With data being captured much faster than traditional missions due to the transitory nature of the electron diffusion region, the ability to compress images for ground transmission will save both time and power, augmenting performance of the spacecraft and instruments over the duration of the mission.

J. Russell Carpenter, PhD

Navigation and CA Lead, MMS

Code: 595

Years with NASA: 28

Education: Ph.D., Aerospace Engineering

Can you give us a brief introduction to your career at NASA Goddard?

In the early to mid 1990s, NASA was doing a lot of experiments with GPS, which was just starting to be minimally operational, and early experiments were being done at Goddard, JSC and JPL. A lot of us were going to the same conferences. I started out coming to Goddard and wanting to do a one year rotation. My immediate supervisor was supportive but the division chief was opposed, which made me mad. The administrator at the time, Dan Goldin, under the reinventing government initiative, was trying to move younger people up in the organization. For every person recruited from one of the code-M centers, he'd provide a billet, and offered the use of NASA-1 executive jet for recruiting. A group of Goddard people flew down to JSC and said I could move if I wanted to. I've been here ever since.

I've been working on MMS for a long time. When I came to Goddard in 1998 there was a big push to invest in formation flying development, so I spent a lot of time on various projects for relative flying. I supported a lot of efforts on EO-1, which was the first formation flying experiment, and I've done a lot of GPS support, selecting vendors and such. I haven't had a significant role in a flown mission until MMS. At JSC I worked on a lot of shuttle missions—mainly rendezvous missions with GPS experiments.

What is the difference between GEODE (GPS-Enhanced Orbit Determination Experiment) and GEONS (Goddard Enhanced On-board Navigation System)?

GEODE was going to fly on the 1996 Lewis mission, which didn't make it into orbit; and then Clark was cancelled. There were several parallel efforts in that time to do GPS navigation. We got started on the Extreme UV explorer using Doppler timing from TDRS and ground stations. That became the TDRS navigation system, still used by TERRA. There was a GPS version of the software which flew on EO-1 (GEODE light). We combined all the variations of on-board software and some celestial navigation software into GEONS, starting about 2001 or so.

Engineers install the Navigator module into the thermal vacuum chamber for thermal cycling tests.

Are there any commercial applications for this technology?

It has been licensed quite a bit; Orbital and Ball use it. Sourci and Calypso, ITT, a number of small companies—too many to list—through things like SBIR. A lot of the CubeSat companies are licensing it as well. GEONS itself is mainly useful for spacecraft, probably not aircraft.

Conrad Schiff, also interviewed in this issue, suggested I ask about the statistically realistic way of mitigating collision risk. What is that all about?

That was something we never expected to be a big problem. Obviously, we fly in a pretty tight formation; 10 km sounds pretty far apart, but we also have very long wire booms, over 120 meters tip-to-tip. Although we have on-board navigation, we don't use it for real-time control; we're locked into a maneuver schedule. It turns out that to have our tetrahedron at apogee we may wind up with very close approaches at perigee. If we didn't do anything, the probability of getting within the width of the wire booms was on the order of one in one hundred. There are simple things to reduce that risk: we screen our maneuvers to make sure the risk is minimal, but also have to work with the risk of an error in a maneuver, error in attitude, hot or cold thrusters. We realized that we needed to take a different view of conjunction assessment.

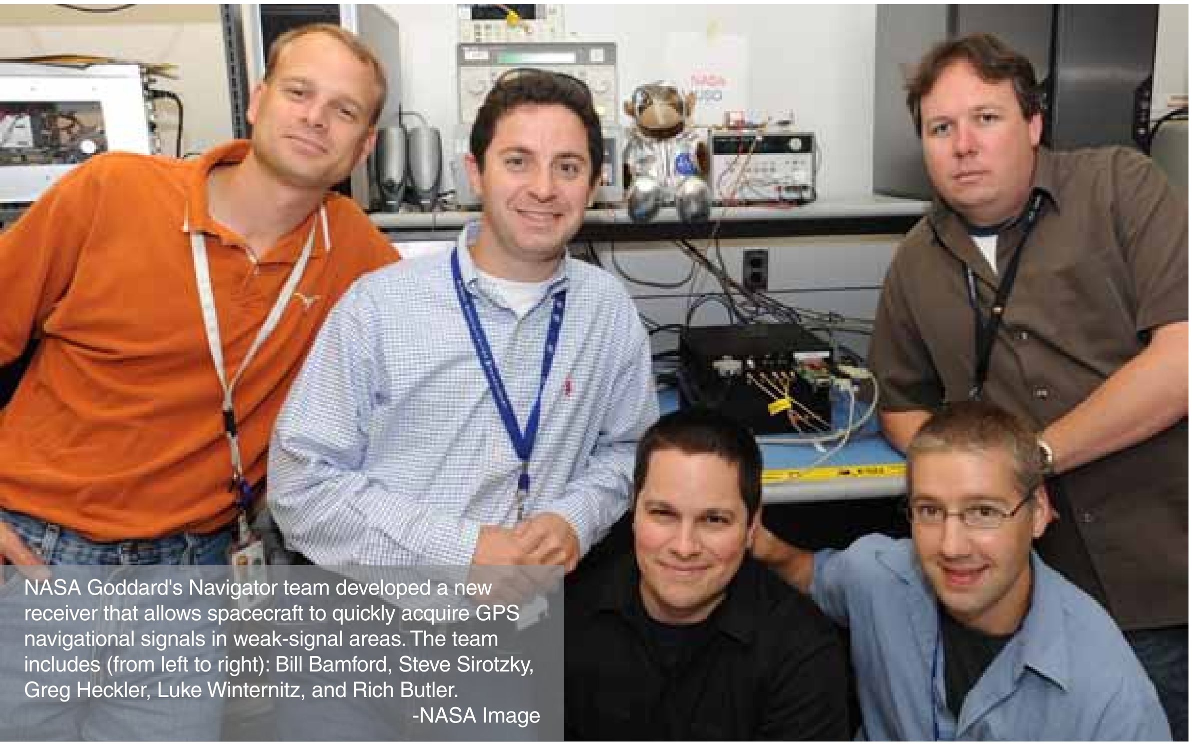
Typically, you just look at distance and decide if it's too close you have to maneuver. Two main mistakes can be made: missed detection or false alarm. The usual way focuses on the first, but with MMS we need to balance false alarms against missed detections—otherwise we could run out of fuel. Checking the literature we couldn't find anyone had dealt with this, but looking at industry we found the Wald sequential probability test, which is used for screening parts. It's a pretty black-and-white thing. We have more of a continuum of possibilities which led to a very elegant result after about 5 years of work. We're the only group doing that now, though I suspect the ISS and TERRA groups are probably backing into doing something similar. We've had MMS encounters with Chinese debris already!

Other Innovations we've identified for the MMS mission include high rate electromagnetic sensing, high-altitude GPS navigation and building four spacecraft simultaneously. Is there anything you'd care to add?

One number to show how well GEONS is working: in order to formation fly, you not only need relative position but relative orbit. We need to know the orbital parameters very accurately. The most important is the semi-major axis, which is one half of the long axis of the ellipse. We need to know the difference between the axes to within 50 meters for each spacecraft—out of a 42,000 km semi-major axis in phase one, more than twice that in phase two. Because Navigator is working so well and GEONS can smooth out the noise, we are getting the semi-major axis to within 1-3 meters, far better than expected. Navigator could not do that without GEONS; it gets about 10 meters at perigee, but is too noisy to use at apogee.

Where do see this technology going in the future?

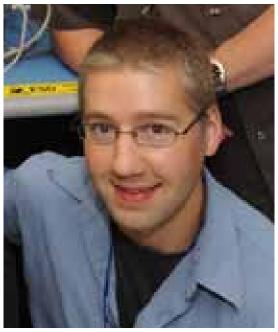
What does this mean for the future? GPS is well accepted for LEO missions, and some GEO missions starting to get on board. Beyond GEO, we never expected GPS to catch on. MMS is a special case because we have an elliptical orbit. TESS came to Goddard recently. Its perigee is higher than our phase one apogee, and the TESS apogee is beyond the Moon. I would never have thought it could use GPS, but based on the results we're getting, I think GPS/GNSS can be used by any mission in Cislunar space. That means missions wouldn't require use of the DSN for navigation. You still need it for communications, but can free up bandwidth for high-rate communications, save money, and increase mission flexibility.



NASA Goddard's Navigator team developed a new receiver that allows spacecraft to quickly acquire GPS navigational signals in weak-signal areas. The team includes (from left to right): Bill Bamford, Steve Sirotzky, Greg Heckler, Luke Winternitz, and Rich Butler.
-NASA Image

Luke Winternitz, PhD

Navigation Systems Architect



Code: 595

Years with NASA: 14

Education: Ph.D., Electrical Engineering

How did you come to NASA Goddard; and what projects have you worked on before MMS?

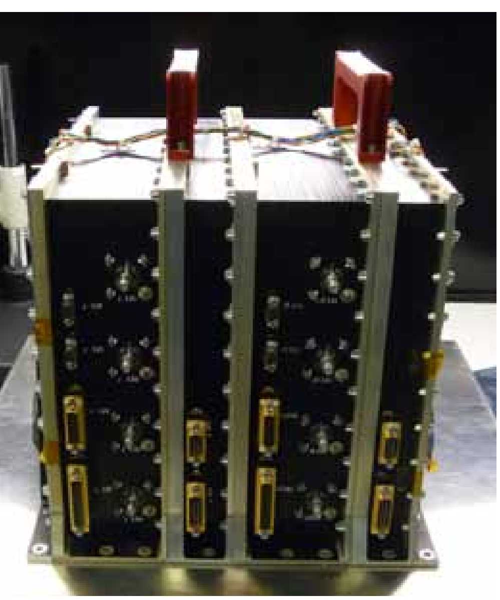
I got the job at Goddard by coincidence. I interviewed out of school, got redirected a couple of different places at NASA, and finally got to code 596, which is responsible for guidance and navigation components which go into every spacecraft. We also do in-house development on a lot of stuff.

I've done a lot of smaller research projects but the main one is the Navigator. I'm working on a technology demo mission called Sextant that will be part of Nicer; it's a pulsar navigation system that could be used for planetary and even interstellar missions. The accuracy isn't like GPS, but not bad…at least in theory. We hope to fly aboard Nicer next year.

I see that you led a team that won "Invention of the Year" in 2010 for a GPS Navigator that can work with weak signals. Is that related to the MMS Navigation system?

In the early 2000s, GPS became popular on satellites, and for LEO it's not very different from on the ground—the satellites are all above you. When your orbit goes above the GPS constellation, about half way to GEO, things change. No commercially available receivers would work at the higher altitudes in GEO and highly elliptic orbits. Some receivers were flown on a test basis, and it became apparent that we needed a way to acquire and track weak GPS signals. We also added filtering software to handle situations where the geometry is poor or you can't see enough of the GPS satellites to generate a single-point solution. We exploit the known orbital parameters to continue to get position.

There are good ways to simulate the system on the ground, so you can have the receivers look at signals as we expect them. MMS is our first full-up flight test. Performance so far, about two weeks in, is better than we'd hoped. We're seeing more GPS satellites and that gives us a better position. The receiver has 12 channels. Our simulations predicted that at our highest altitude we might only see 2-3 satellites. Instead, we're seeing 9-12, which is an exciting surprise! Our preflight simulation was conservative. MMS is challenging for two reasons: high altitude and spin stabilization—we had to put four antennas for each of the two receivers on each satellite to maintain continuous track on each signal. That doesn't allow a high gain antenna.



Are there any commercial applications for the Navigator, or other innovations worthy of mention from MMS?

The Navigator has been commercialized. There is a patent on the technology, licensed to Broad Reach Engineering for a commercial version to be used in other spacecraft. We've had a number of milestones this year and last; receiver development goes back about two years. It was picked up on two missions: GPM and MMS. It flew on GPM. We transferred some of the technology to Honeywell, who built the receiver for the Orion CEV capsule, and it flew for the first time last year. In that application, the fast acquisition capability is significant to accurately locate the spacecraft for final approach corrections after reentry blackout.

What's the biggest challenge you've faced on MMS?

Trying to do weak signal GPS at the highest altitude ever, on a spinning spacecraft was a pretty extreme challenge! Executing a first-off design, we had the usual hiccups but so far it looks really good on orbit. It's really a huge team effort, and we had a fantastic team working on this. I'm the Navigator Architect, Ken McCoy is the product lead; GEONS is a completely separate development. Probably 50 people made significant contributions.

Networking and Outreach

ITPO staff members Dennis Small and Dale Clarke speak with an attendee at the annual code 600 SED New Year's Poster Party.

8th Annual Sciences & Exploration Directorate New Year's Poster Party

January 28, 2015, Greenbelt, MD

NASA Goddard's Innovative Technology Partnerships Office (ITPO) participated in the 8th Annual Sciences & Exploration Directorate (SED) New Year's Poster Party, held in NASA Goddard's Building 28 atrium. This annual event brings together Goddard's Earth and space scientists, along with invited presenters from the Applied Engineering and Technology Directorate (AETD), to display their posters from 2014 meetings. ITPO staff members spoke with attendees about partnerships, licensing, New Technology Reporting (NTR) benefits and SBIR/STTR successes.

ITPO Senior Technology Manager Darryl Mitchell speaks with an attendee at the 2015 ARPA-E Energy Innovation Summit.

ARPA-E Energy Innovation Summit

February 9-11, 2015, National Harbor, MD

NASA participated in the 2015 ARPA-E Energy Innovation Summit at the Gaylord National Hotel and Convention Center in National Harbor, MD on February 9 - 11, 2015. Goddard's Innovative Technology Partnerships Office was on hand along with representatives from NASA Glenn Research Center, Johnson Space Flight Center, Kennedy Space Center and NASA Ames Research Center. The ARPA-E Energy Innovation Summit is an event dedicated to transformative energy solutions, bringing together thought leaders from academia, business, and government to discuss cutting-edge energy issues and facilitate relationships to help move technologies into the marketplace. There were approximately 3,000 summit attendees who provided a steady stream of showcase attendees. NASA received several inquiries in specific areas such as electronics, AeroPod technology, solar energy, and batteries, to name a few.

Association of University Technology Managers (AUTM) Annual Meeting

February 22-25, 2015, New Orleans, LA

NASA Goddard's Innovative Technology Partnerships Office (ITPO) attended the annual meeting of the Association of University Technology Managers (AUTM) in New Orleans, LA. This year's meeting saw more than 1,900 technology transfer professionals from around the world and featured networking, professional development, and sessions with national and international experts on trends in technology transfer. AUTM's members represent intellectual property managers from more than 300 universities, research institutions, teaching hospitals, businesses, and government agencies.

Disclosures and Patents

Disclosures

2015 January-March

Spacecraft Thermal Control System not Requiring Power

LTAS Source Slaving Selector (LS3) Analyzer

An interactive visual analytics data mining tool and applications to spacecraft mission design

Method for detecting super-thin clouds with polarized light

MegapixelMercury Cadmium Telluride Focal Plane Arrays for Infrared Imaging out to 12Microns

System to perform radio frequency interferometry using optical fiber sensing signal processing techniques.

NetAcquire Status

Flood Dashboard 2.0

Parallel Nonlinear Optimization for Astrodynamic Navigation

Hybridspectral Radiometer Systems to Support Ocean Color Calibration and Validation

Broadband Reflective Coating Process for Large FUVOIR Mirrors

9-Meter Slaving System

"Integrated Modeling, Analysis, and Verification for Space Missions"

A Portable source of lattice trapped and ultracold atoms

Goddard Mission Services Evolution Center Architecture Application Programming Interface (GMSEC) Architecture API) with CompatC2 Secure Module and Messaging Interface Standardization Toolkit (MIST) Module [Software Release Version 3.7]

Earthdata Search

High power W-band solid-state amplifier design

Nanocrystalline Mg-doped Zinc Oxide Scintillator for UV detectors

Multi-wavelength pumping of laser materials with high aspect ratio

Self Sustained Magnesio Thermic Combustion (SSMTC) Assisted Few Layer Graphenes (<4 layers) for Thermal Management Applications

Desktop Status

Process for Fabrication of Superconducting Vias for Electrical Connection to Groundplane in Cryogenic Detectors.

Accelerometer for Space Applications Based on Light-Pulse Atom Interferometry

GMSEC Test Environment Generator and Executor Tool

A Robust Waveguide Millimeter Wave Noise Source

Efficient in-bond diode-pumped Q-switched SSL for methane detection

An Invariant Manifold Analysis Tool (IMAT)

Boron Nitride Nano Tubes for Thermal Management Applications.

Iron Sheilding to Increase Field Intensity and Unifomity of HTS ADR Coils

Low-Frequency All Digital Radar (ADR) for Biomass and Ice-sheet Investigation

Bonded sapphire gasket

Pergola - Reflector Based Approach to Illuminating Solar Arrays for Missions that Approach the Sun Closer than 1 Astronomical Unit

High Accuracy CO2 Instrumentation for UAVs

A method for connecting NTSC cameras to the SPDM OTCM Umbilical Video Input

Real-time Assimilative Models for Precise Specification of the Space Environment

Unmanned Aerial Vehicle Diode Laser Sensor for Methane

Rad-Hard Sigma-Delta 3-channel ADC for Fluxgate Magnetometers

Fully-Sampled Magnetic-Coupled Multi-Mode Beam Combiner

M-TEC - Non-Contact Deflectometry Metrology Technology for Reflective Surfaces

GLOBE Program's Citizen Science Cloud App for Android

Compensation of Temporal Latch Delay for Temperature and Voltage Variations

Mounting of a Small Diameter Laser Gain Medium

Laser beam expander with adjustable collimation

Landsat Water Detection Tool

A Machine Learning Workflow for Land Classification with Remote and Terrestrial Sensor Data

Pin Alignment Fixture

"SpaceCube ""Next"""

LTAS Simulator

Fabrication of coronagraphy petal-shaped masks for the Laser Interferometry Space-based gravitational-wave Antenna (eLISA) telescope using Photolitography and Wire-EDM

Method for Fabricating Nano-Structures

LTAS Source Slaving Selector (LS3)

"Compact, light weight and efficient solid-state laser"

Patent Applications

2015 January-March

"Meta-material Blocking Filter with Low Geometric Inductance"

Provisional Patents

2015 January-March

Improved Performance of the JPEG Estimated Spectrum Adaptive Postfilter (JPEG-ESAP) and Comparisons to JPEG-2000 Images

Radiation Hardened 10BASE-T Ethernet PHY

U.S. Patents Issued

2015 January-March

V-Assembly Dual Head Efficiency Resonator (VADER) Laser Transmitter U.S. Patent Number 8,958,452

Autonomic Autopoiesis U.S. Patent Number 8,983,883

Enhanced adhesion multiwalled carbon nanotubes on titanium substrates for stray light control U.S. Patent Number 8,976,362

Nanostructure secondary mirror apodization mask for transmitter signal suppression in a duplex telescope. U.S. Patent Number 8,963,068

"Autonomic and Apoptotic Cloud, Autonomic and Apoptotic Grid, Autonomic and Apoptotic Highly Distributed System" U.S. Patent Number 8,983,882

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